Testing General Relativity with Black Hole X-ray Data

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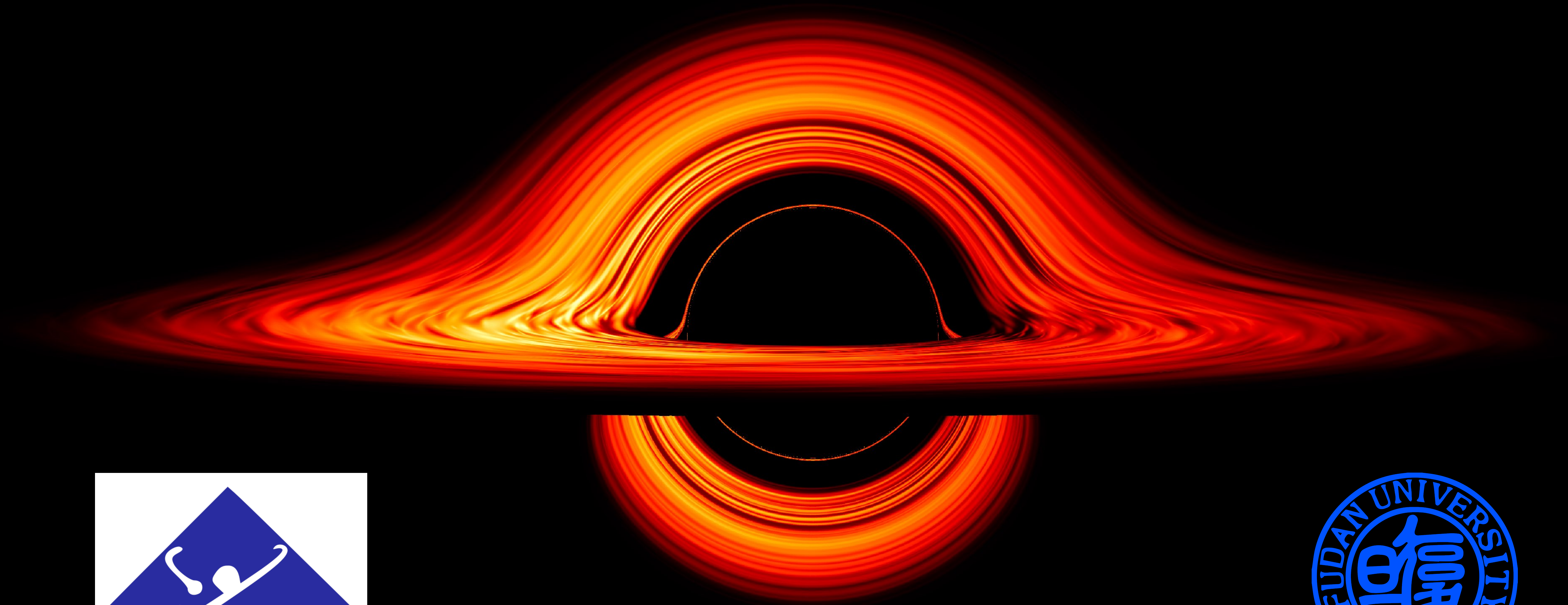


XXXV International Workshop on High Energy Physics
Protvino, Russia (28 November - 1 December 2023)

Motivations

Tests of General Relativity

- 1915 → General Relativity (Einstein)

- 1919 → Deflection of light by the Sun (Eddington)
- 1960s → Solar System experiments
- 1970s → Binary pulsars

- 2000s → Cosmological tests

Tests in weak gravitational fields

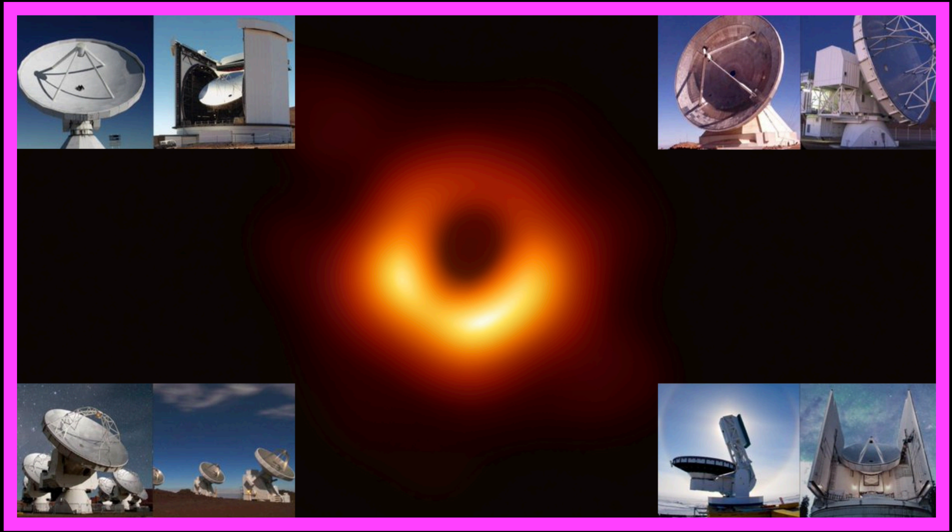
Tests on large scales

Tests of General Relativity

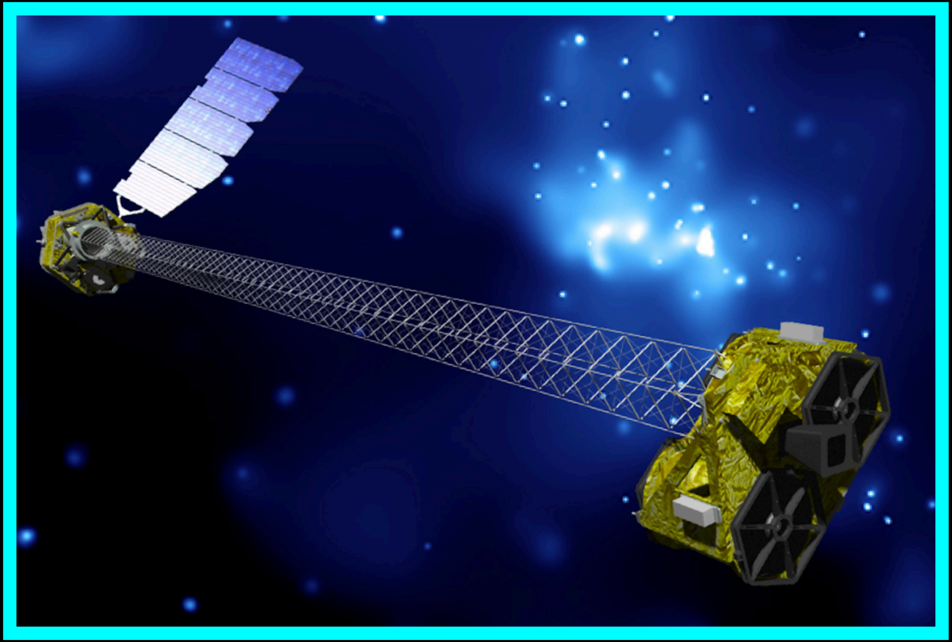
- 2010s → Black holes, neutron stars

Tests in strong gravitational fields

GW Data



VLBI Data



X-ray Data

Black Holes

Black Holes in General Relativity

- No-Hair Theorem: in 4D General Relativity, black holes are fully characterized by a small number of parameters: M, J, Q
- Uniqueness Theorem: in 4D General Relativity, black holes are only described by the Kerr-Newman solution
- Uncharged black holes are described by the Kerr solution

Beyond General Relativity

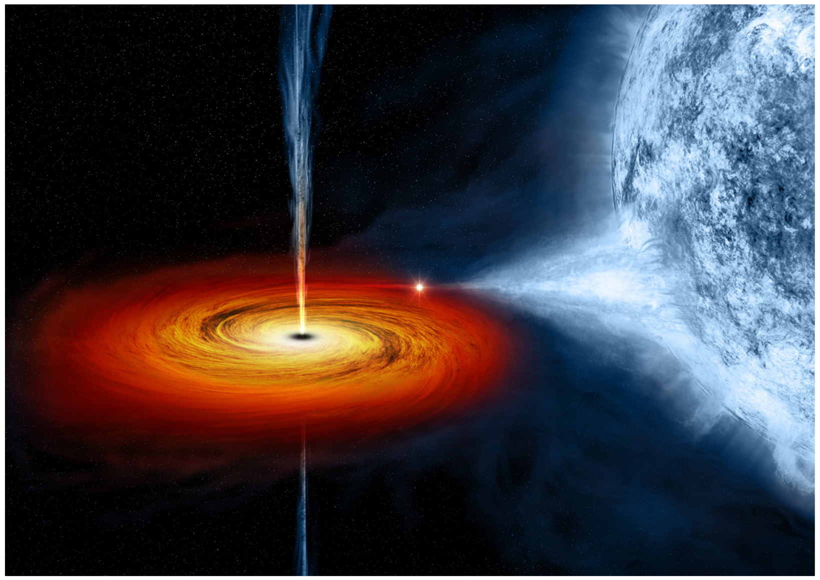
- Modified theories of gravity:
  - Einstein-dilaton-Gauss-Bonnet gravity
  - Chern-Simons gravity
  - Lorentz-violating theories
  - ...

- Macroscopic quantum gravity effects (information paradox):
  - Mathur (Fuzzballs)
  - Dvali & Gomez
  - Giddings
  - ...

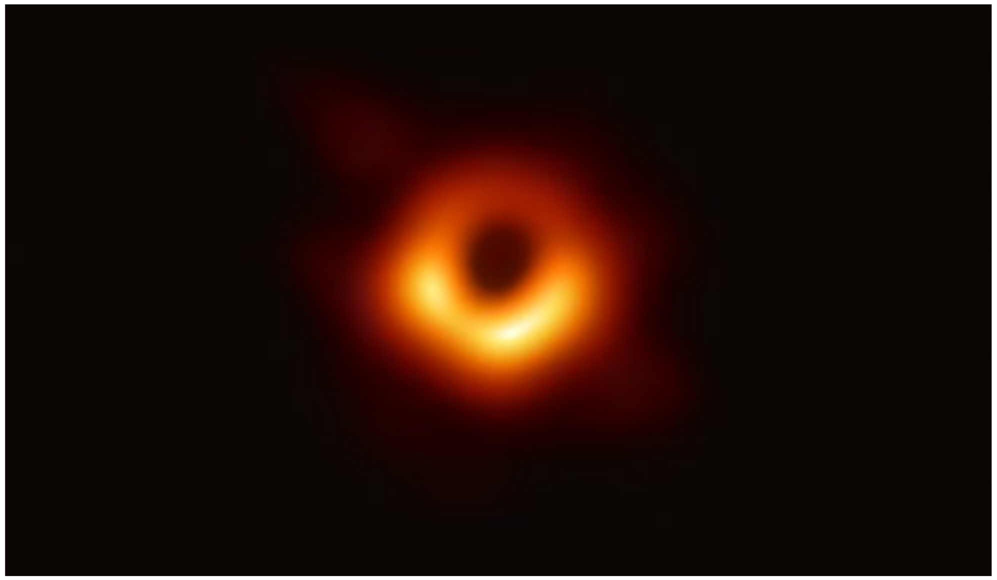
- Presence of exotic matter:
  - Hairy black holes (Herdeiro & Radu)
  - ...

Astrophysical Black Holes

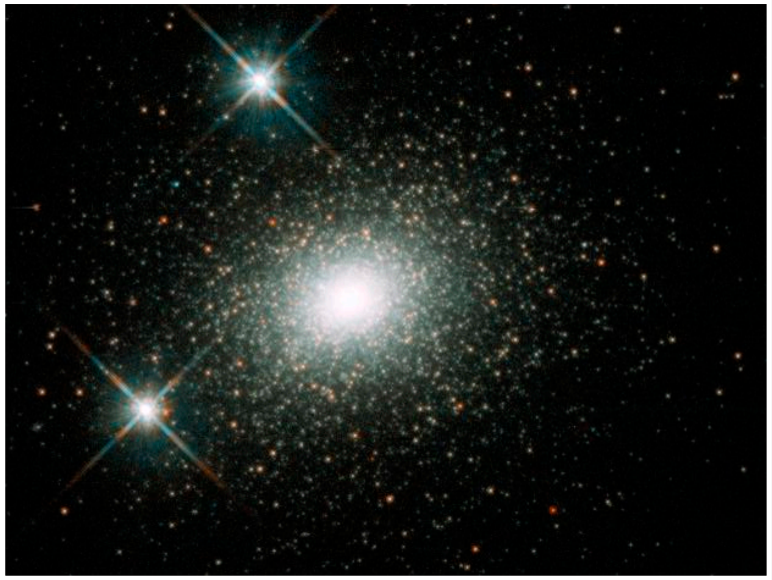
Stellar-mass black holes
(~3-100 $M_\odot$)



Supermassive black holes
(~10^5-10^{10} $M_\odot$)



Intermediate-mass
black holes



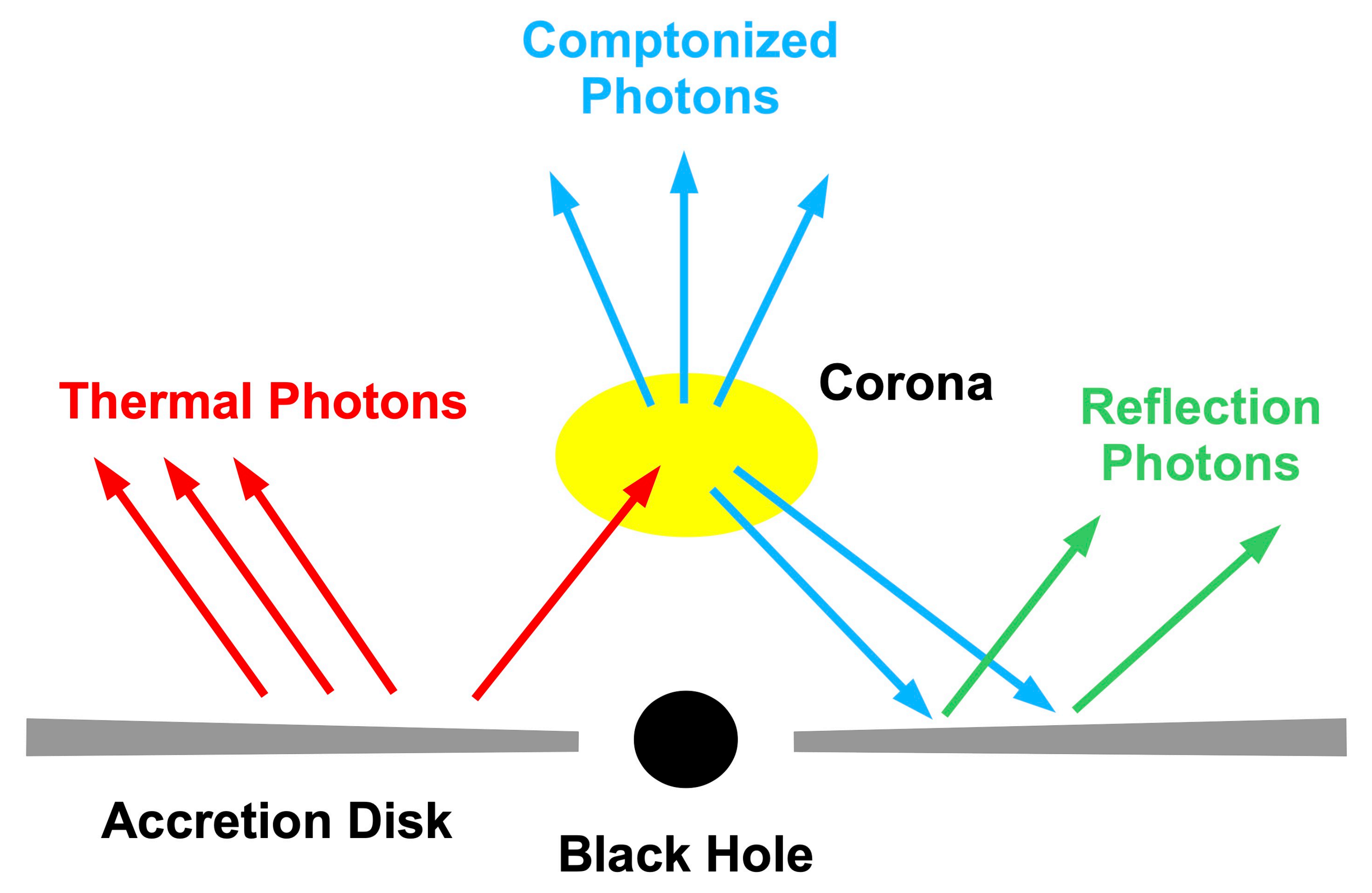
Astrophysical Black Holes

It is remarkable that the spacetime metric around astrophysical black holes formed from gravitational collapse of stars/clouds should be approximated well by the "ideal" Kerr metric

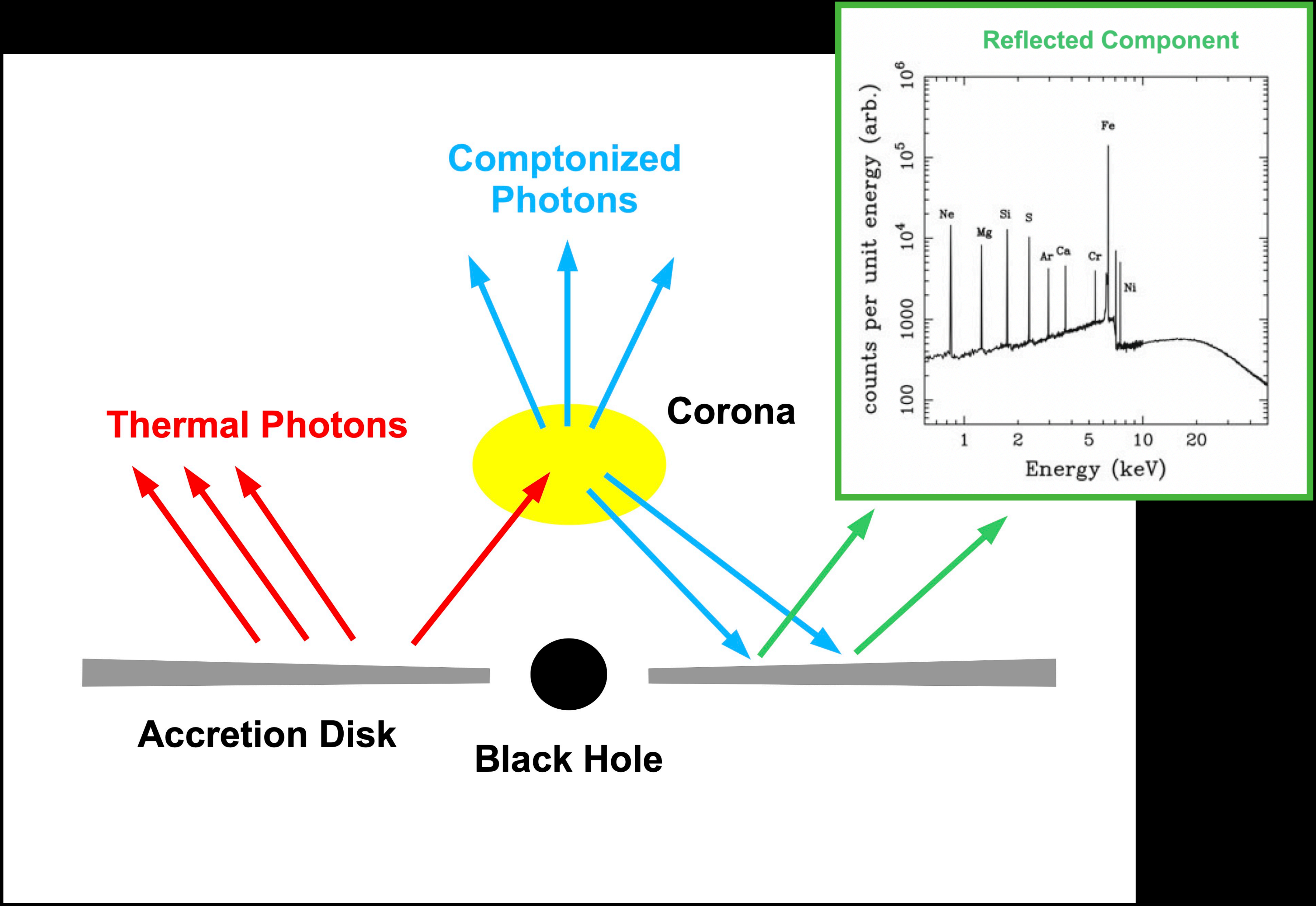
- Initial deviations → Quickly radiated away by GWs
- Accretion disk, nearby stars → Negligible
- Electric charge → Negligible

Disk-Corona Model

Disk-Corona Model



Disk-Corona Model



Comptonized Photons

Thermal Photons

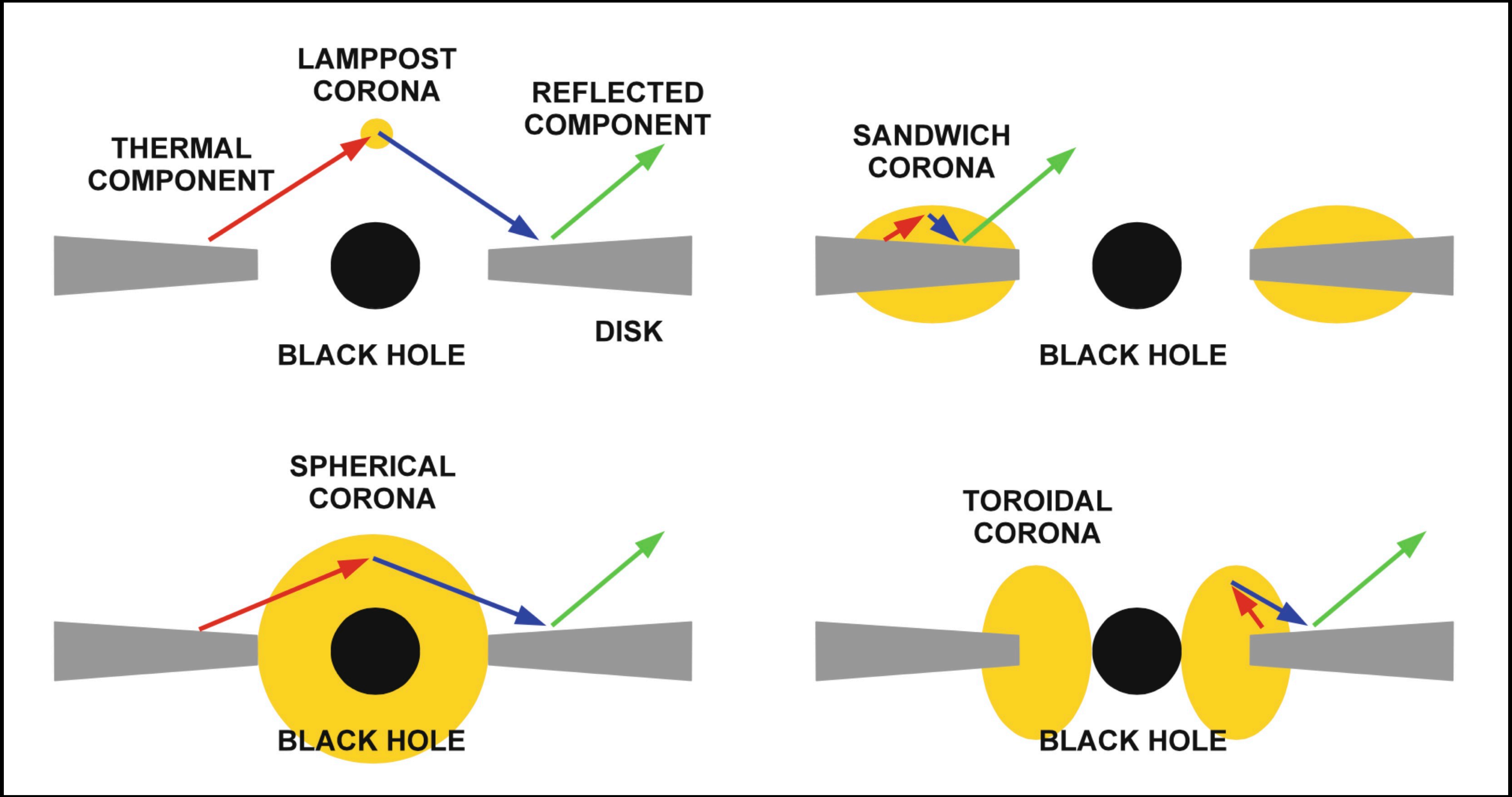
Corona

Accretion Disk

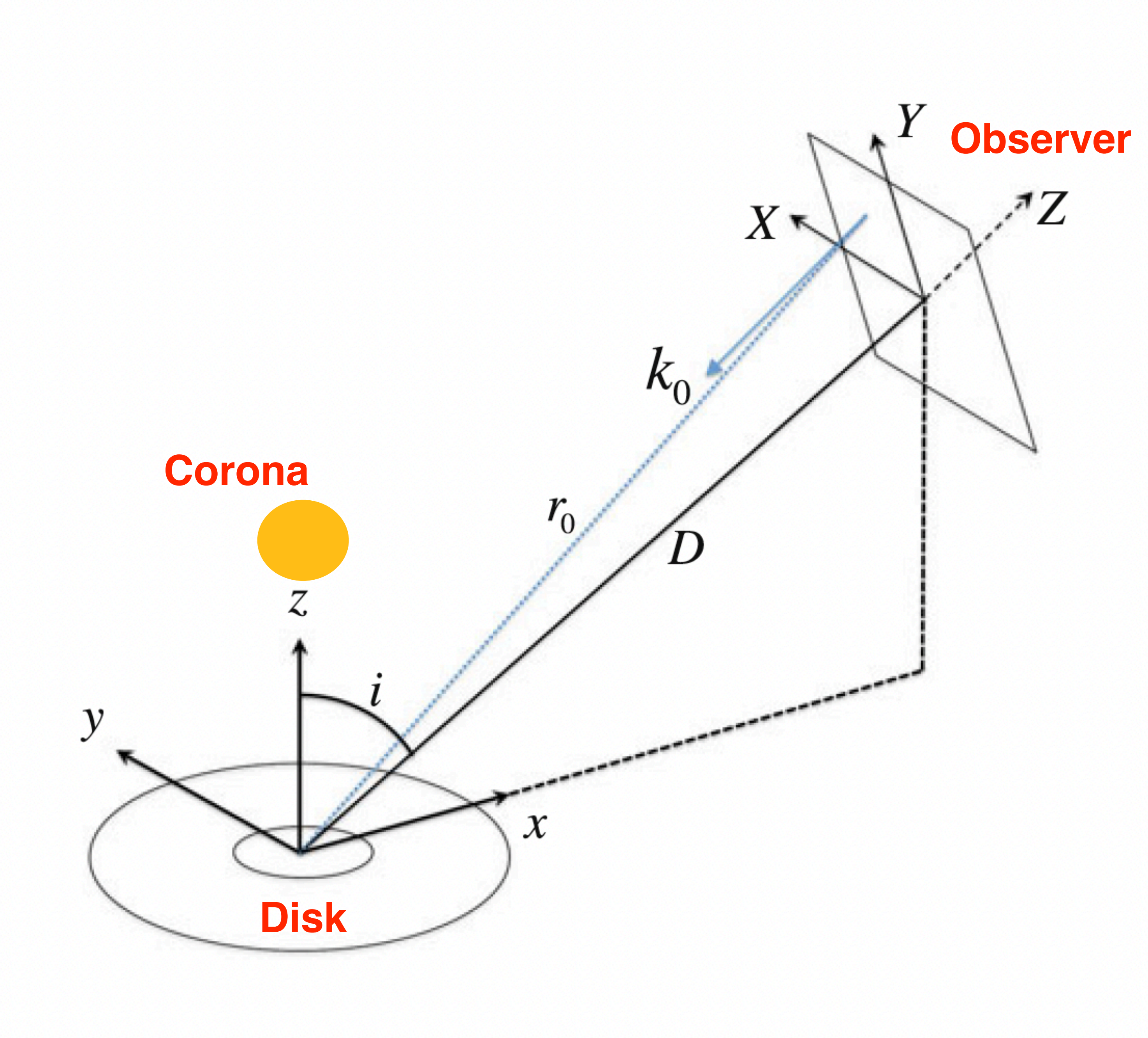
Black Hole

Reflected Component

Coronal Geometries



Synthetic Spectra



Synthetic Spectra

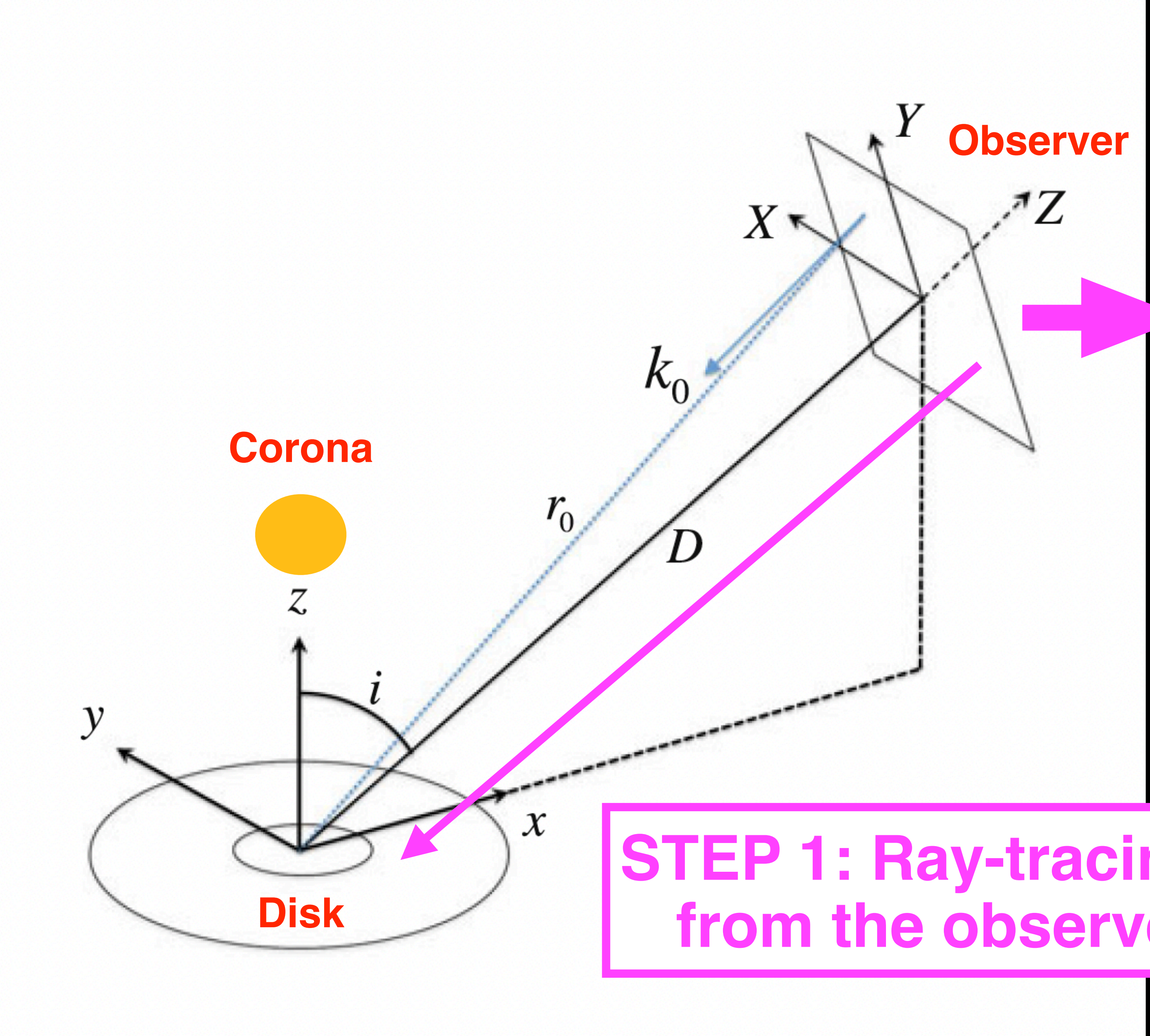
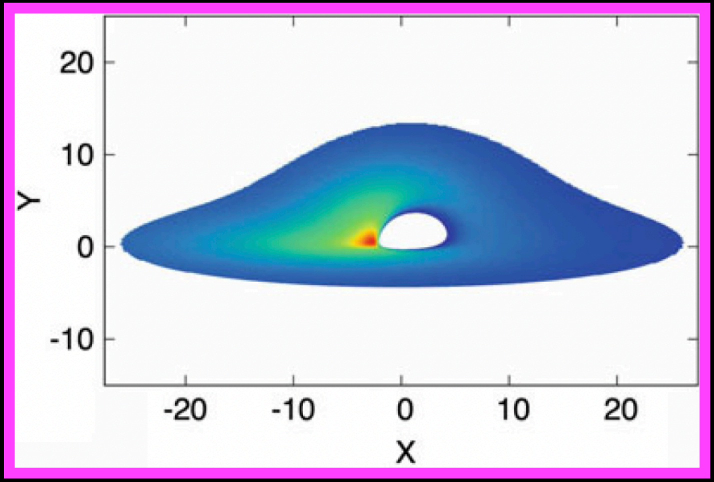


Image of the accretion disk

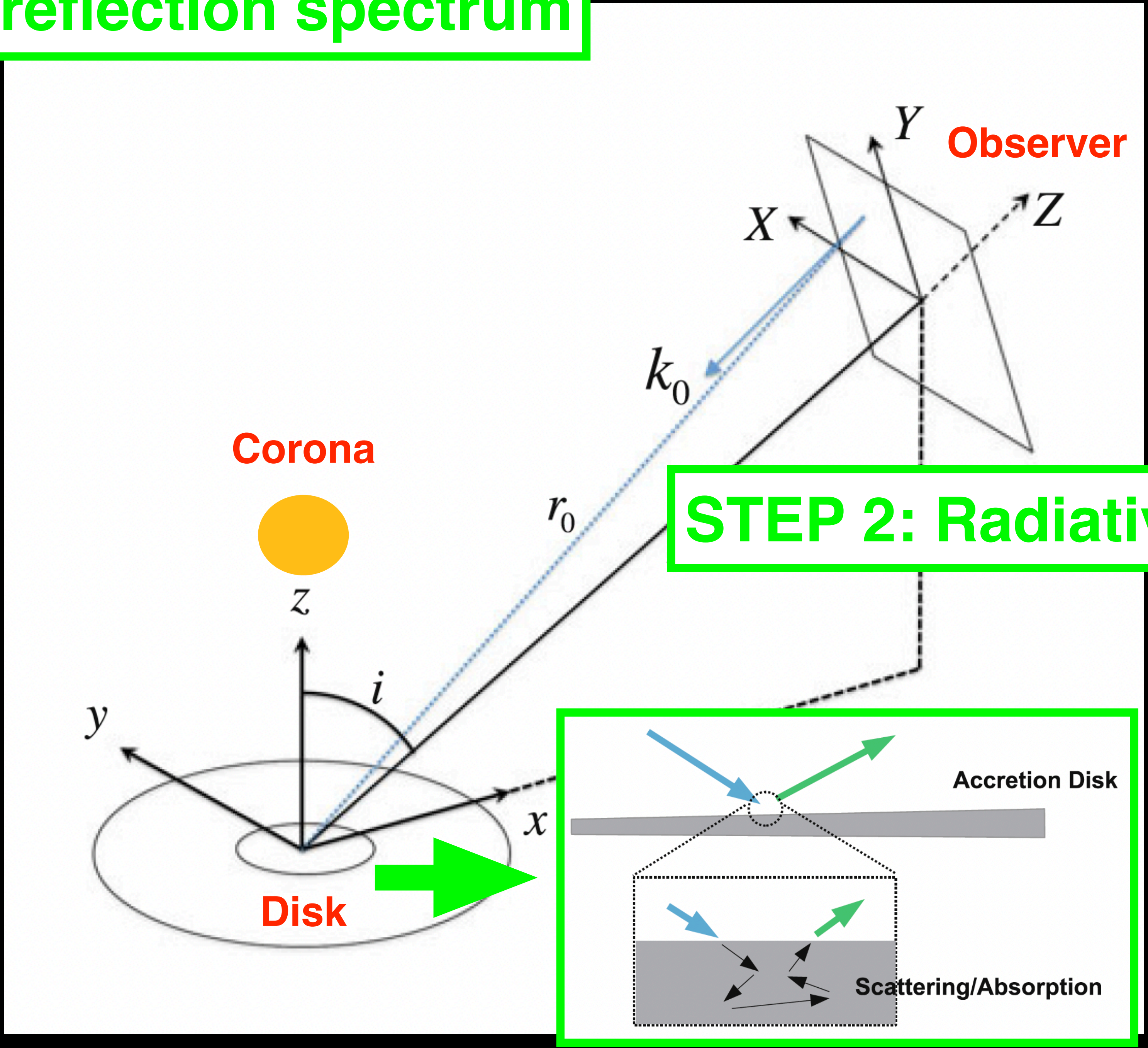


Every point on the image
is characterized by
its redshift factor *g*

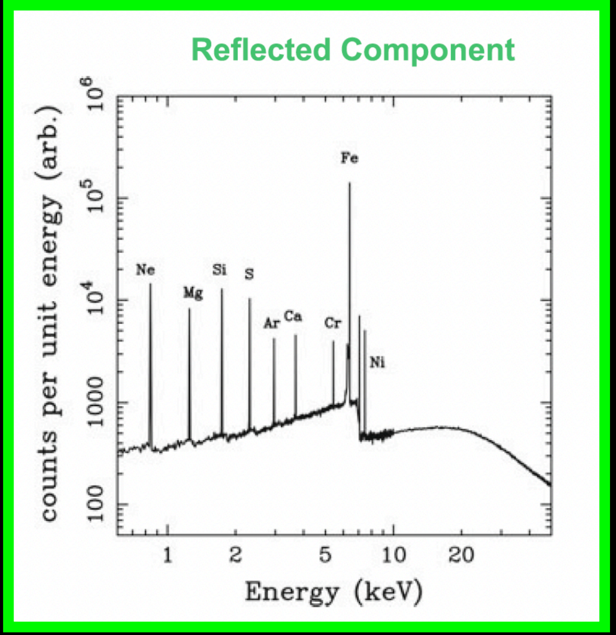
STEP 1: Ray-tracing calculations from the observer to the disk

Synthetic Spectra

For reflection spectrum

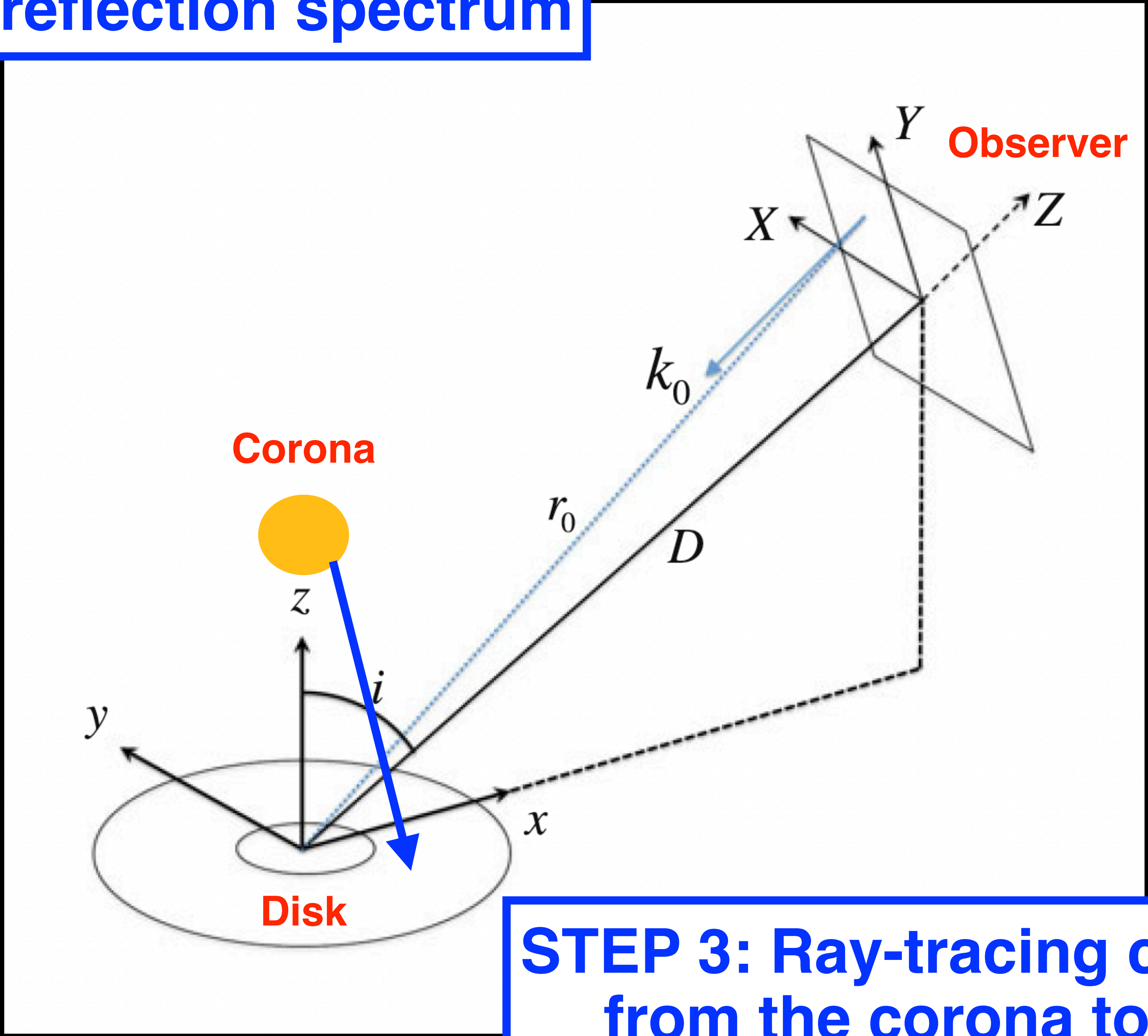


STEP 2: Radiative transfer equations



Synthetic Spectra

For reflection spectrum



STEP 3: Ray-tracing calculations from the corona to the disk

Synthetic Spectra

- Photon motion (from the observer to the disk)
- Particle motion on the disk
- Radiative transfer equations (atomic physics, fundamental constants)
- Photon motion (from the corona to the disk)
- Particle motion on the disk

- Accretion disk model
- Corona model

Testing Black Holes
with X-ray Data

Synthetic Spectra

- Photon motion (from the observer to the disk)
- Particle motion on the disk
- Radiative transfer equations (atomic physics, fundamental constants)
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We can test the Kerr metric

We can test the geodesic motion

Synthetic Spectra

- Photon motion (from the observer to the disk)
- Particle motion on the disk
- Radiative transfer equations (atomic physics, fundamental constants)
- Photon motion (from the observer to the disk)
- Particle motion on the disk

- Accretion disk model
- Corona model

We can test atomic physics and the values of fundamental constants in strong gravitational fields

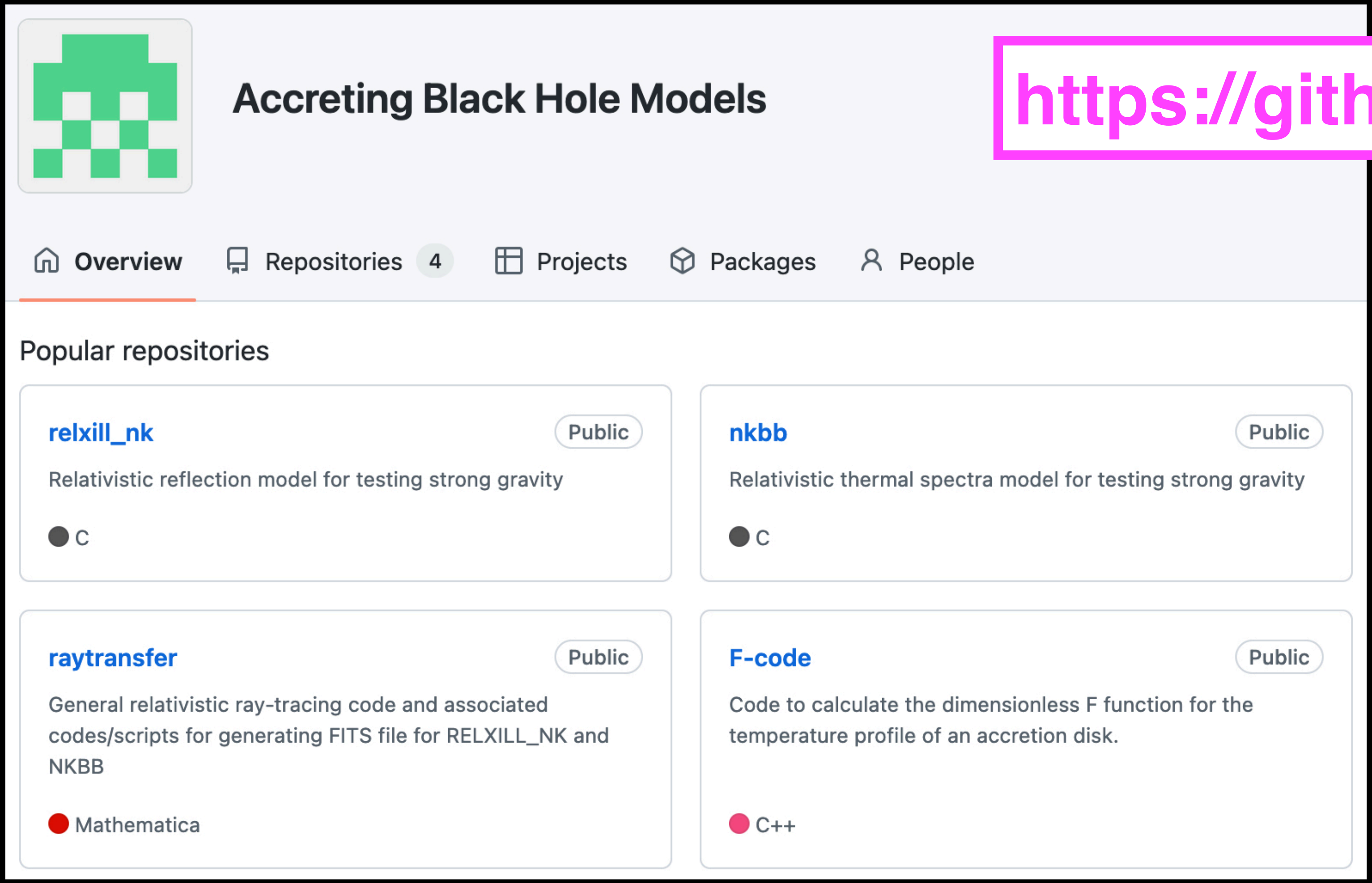
XSPEC Models

- `relxill_nk` (Bambi et al. 2017; Abdikamalov et al. 2019)

  Reflection spectrum for thin accretion disks in stationary, axisymmetric, and asymptotically-flat spacetimes

- `nkbb` (Zhou et al. 2019)

  Thermal spectrum for thin accretion disks in stationary, axisymmetric, and asymptotically-flat spacetimes



Accreting Black Hole Models

https://github.com/ABHModels

Popular repositories

relxill_nk
Relativistic reflection model for testing strong gravity
● C

nkbb
Relativistic thermal spectra model for testing strong gravity
● C

raytransfer
General relativistic ray-tracing code and associated codes/scripts for generating FITS file for RELXILL_NK and NKBB
● Mathematica

F-code
Code to calculate the dimensionless F function for the temperature profile of an accretion disk.
● C++

Strategies

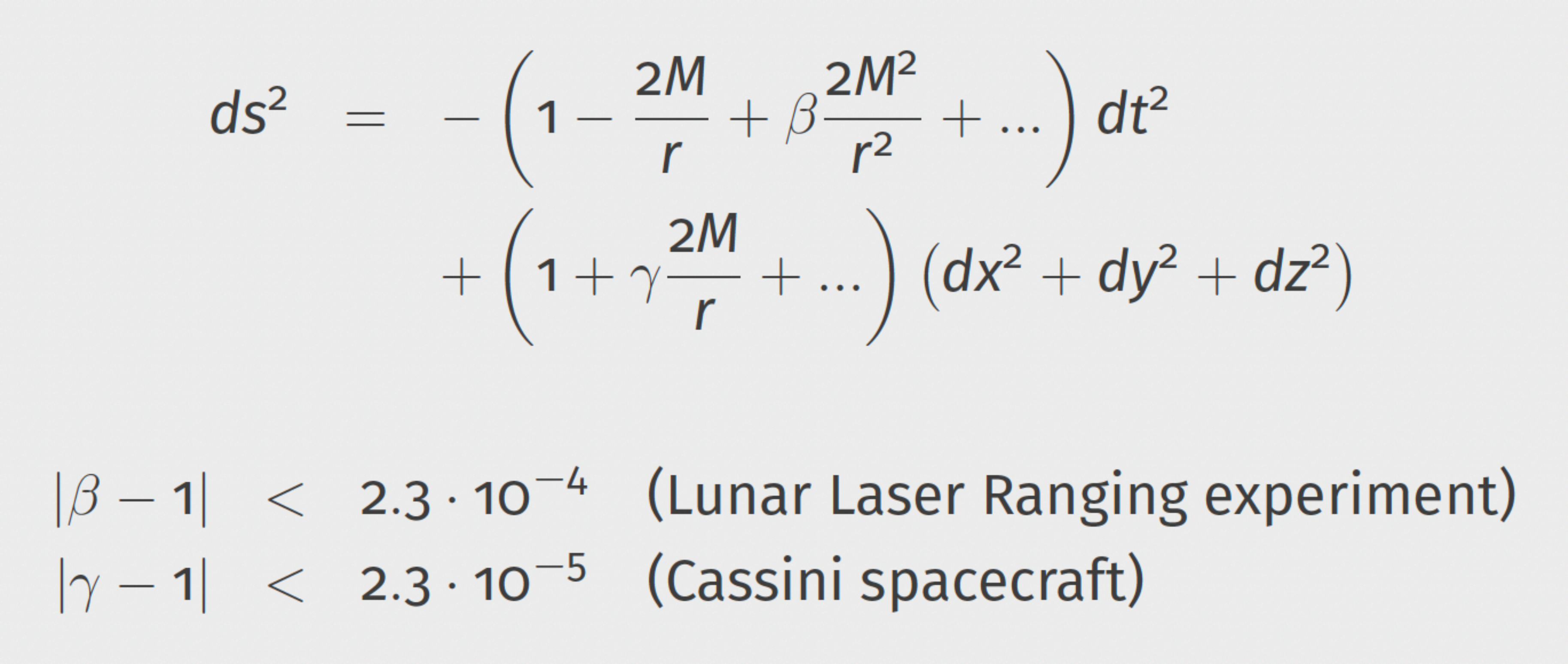
Strategies

- Top-down approach: we test a specific alternative theory of gravity against Einstein’s theory of General Relativity. Problems:
  - There are many theories of gravity...
  - Usually we do not know their rotating black hole solutions...

- Bottom-up approach: we parametrize possible deviations from General Relativity with a number of phenomenological "deformation parameters"

Example: PPN Formalism

- Parametrized Post-Newtonian (PPN) formalism
- Weak field limit: M/r << 1
- Solar System experiments



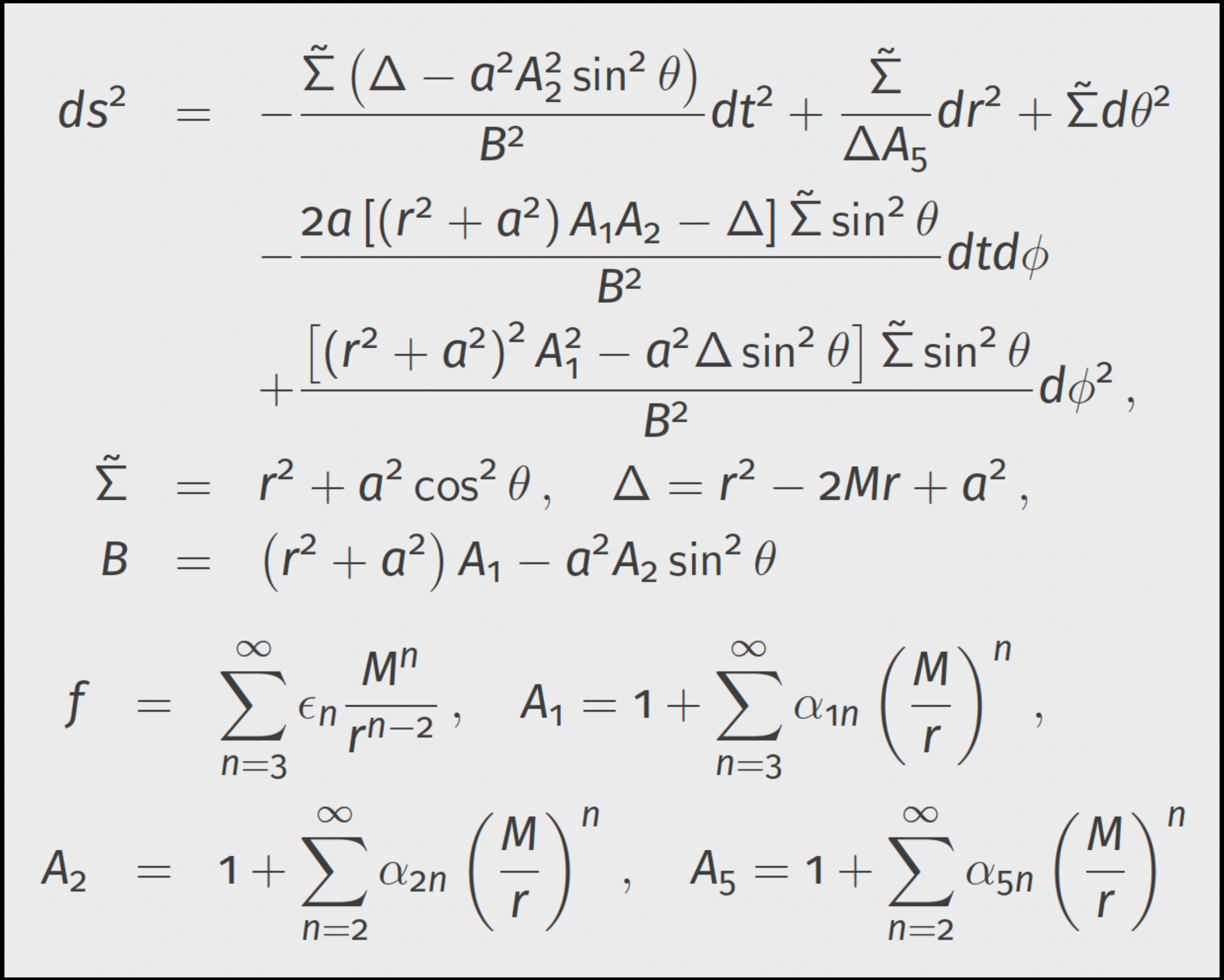
$$
\begin{aligned}
ds^2 &= -\left(1-\frac{2M}{r}+\beta\frac{2M^2}{r^2}+\dots\right)dt^2\\
&\quad+\left(1+\gamma\frac{2M}{r}+\dots\right)\left(dx^2+dy^2+dz^2\right)
\end{aligned}
$$

$$
\begin{aligned}
|\beta-1| &< 2.3\cdot10^{-4} \quad \text{(Lunar Laser Ranging experiment)}\\
|\gamma-1| &< 2.3\cdot10^{-5} \quad \text{(Cassini spacecraft)}
\end{aligned}
$$

- In General Relativity (Schwarzschild metric): β = γ = 1

Example: Johannsen Metric

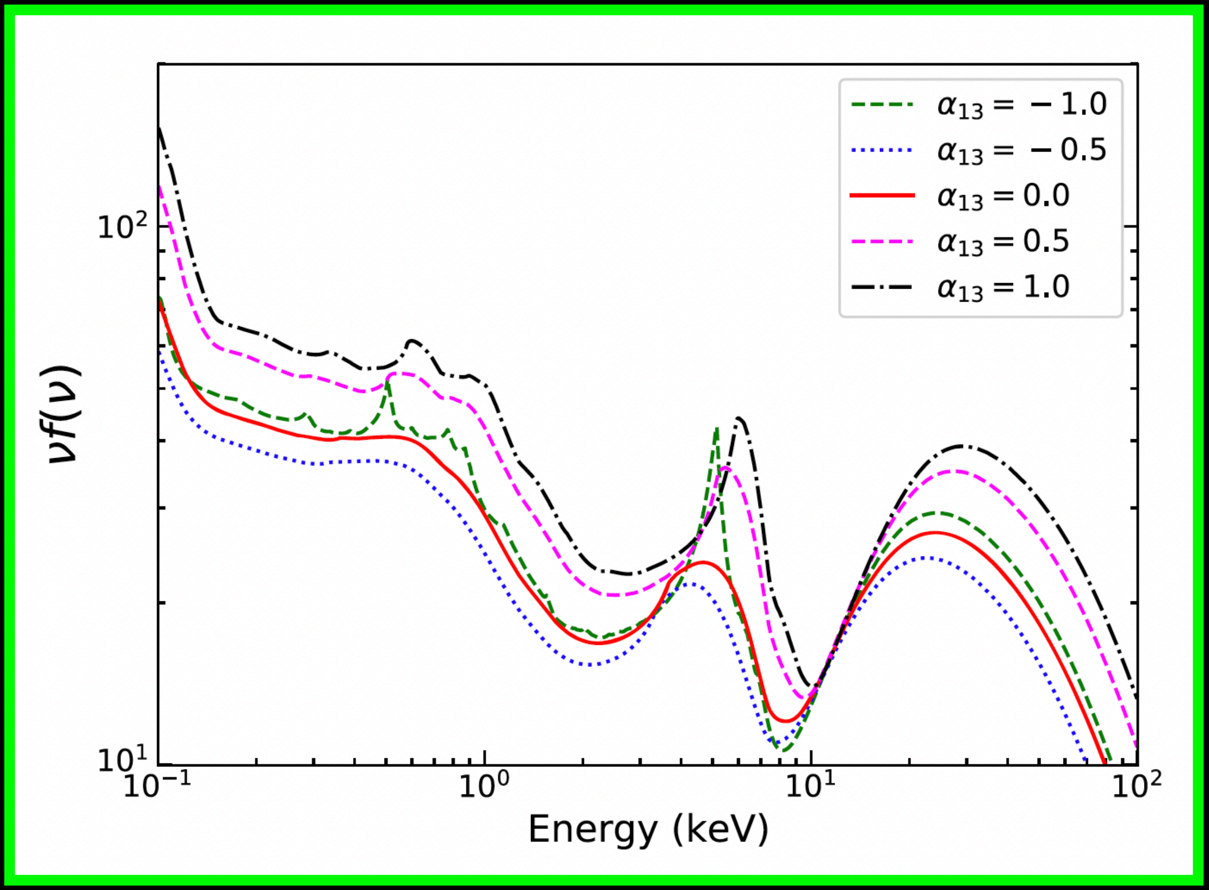
- Several parametric black hole spacetimes proposed in the literature
- Johannsen metric (Johannsen 2013):

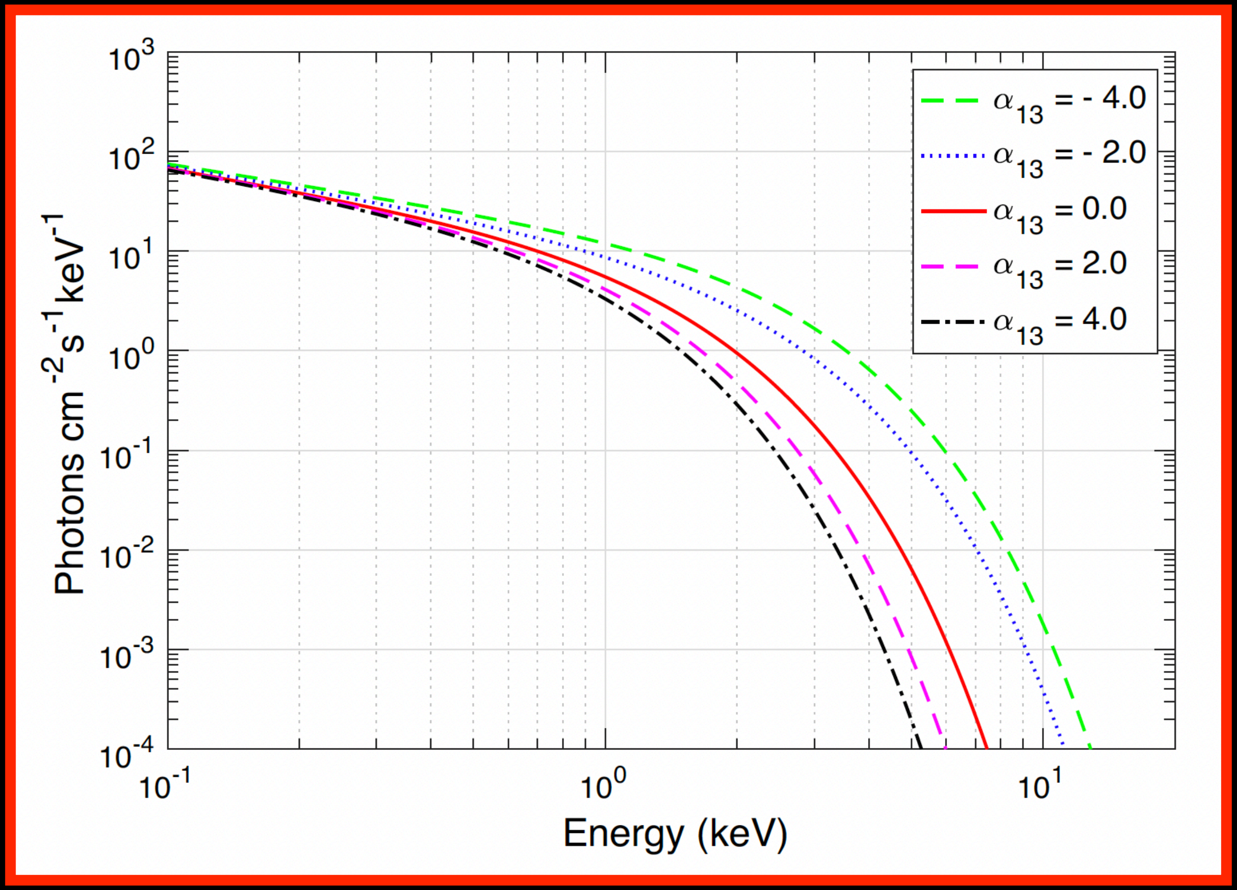


$$
\begin{aligned}
ds^2 &= -\frac{\tilde{\Sigma}\left(\Delta - a^2 A_2^2 \sin^2\theta\right)}{B^2} dt^2 + \frac{\tilde{\Sigma}}{\Delta A_5} dr^2 + \tilde{\Sigma} d\theta^2 \\
&\quad - \frac{2a\left[\left(r^2+a^2\right) A_1 A_2 - \Delta\right] \tilde{\Sigma} \sin^2\theta}{B^2} dt d\phi \\
&\quad + \frac{\left[\left(r^2+a^2\right)^2 A_1^2 - a^2 \Delta \sin^2\theta\right] \tilde{\Sigma} \sin^2\theta}{B^2} d\phi^2 , \\
\tilde{\Sigma} &= r^2 + a^2 \cos^2\theta , \quad \Delta = r^2 - 2Mr + a^2 , \\
B &= \left(r^2+a^2\right) A_1 - a^2 A_2 \sin^2\theta
\end{aligned}
$$

$$
\begin{aligned}
f &= \sum_{n=3}^{\infty} \epsilon_n \frac{M^n}{r^{n-2}} , \quad A_1 = 1 + \sum_{n=3}^{\infty} \alpha_{1n} \left(\frac{M}{r}\right)^n , \\
A_2 &= 1 + \sum_{n=2}^{\infty} \alpha_{2n} \left(\frac{M}{r}\right)^n , \quad A_5 = 1 + \sum_{n=2}^{\infty} \alpha_{5n} \left(\frac{M}{r}\right)^n
\end{aligned}
$$

Example: Johannsen Metric

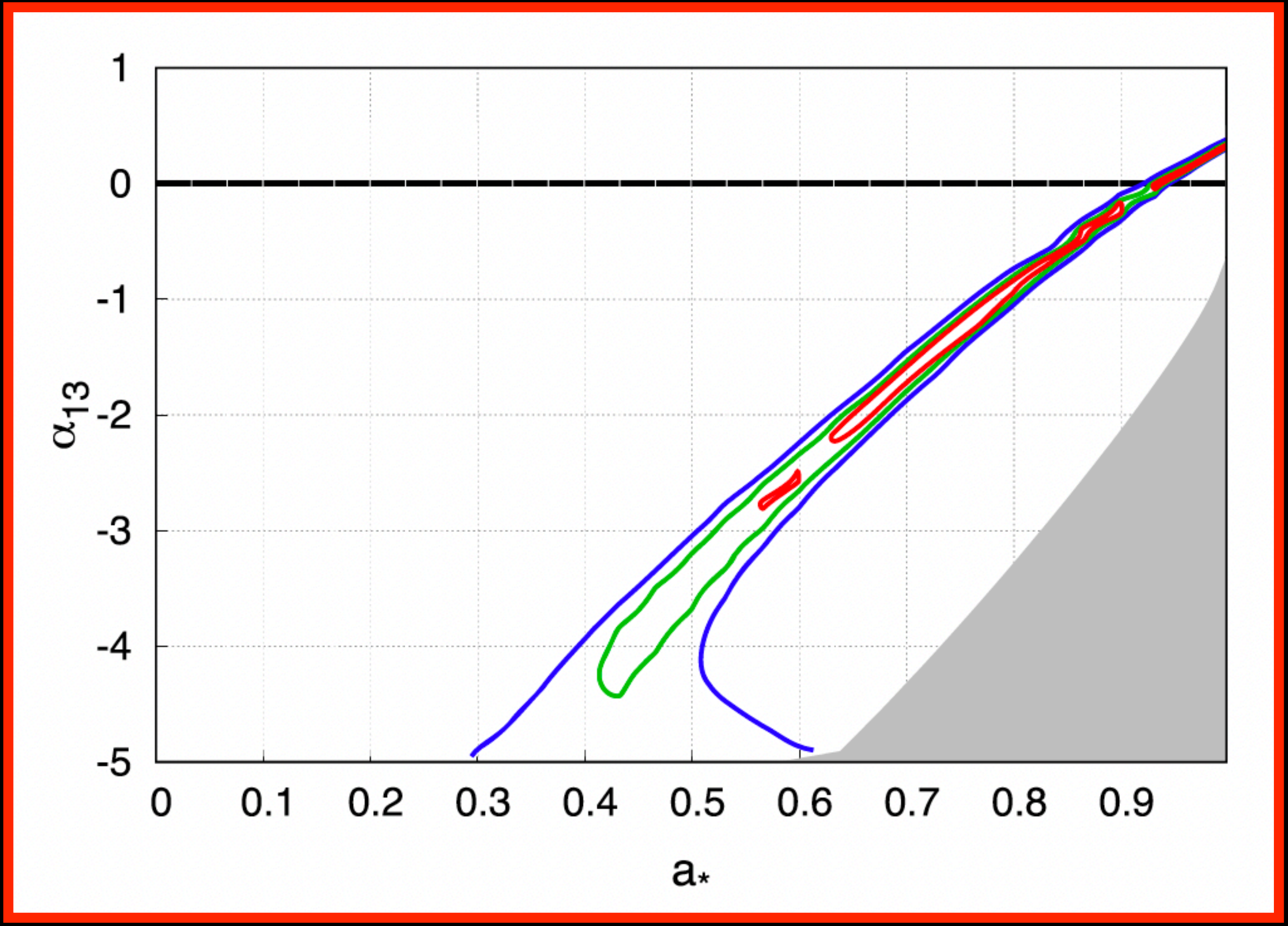


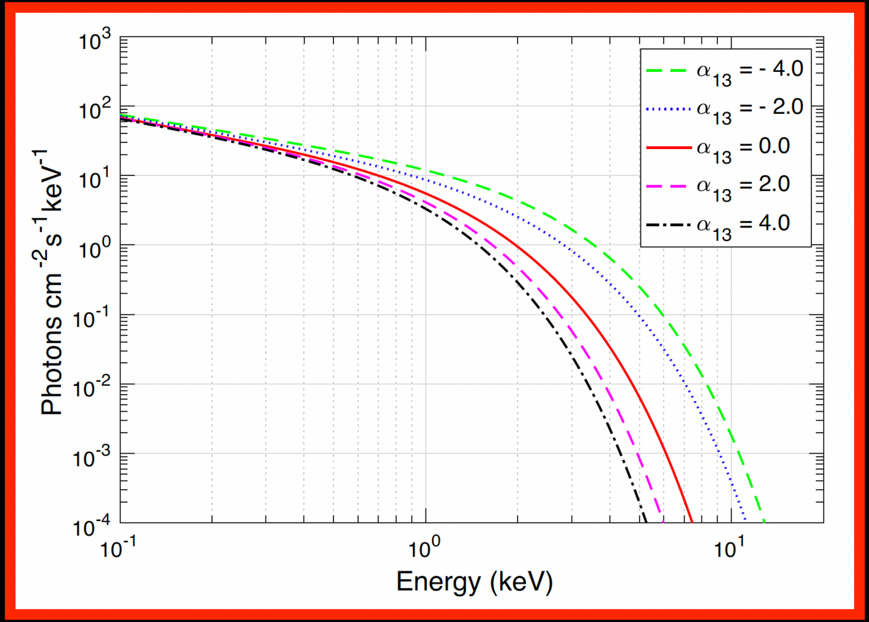


Results:
Agnostic Tests

Analysis of Thermal Spectra

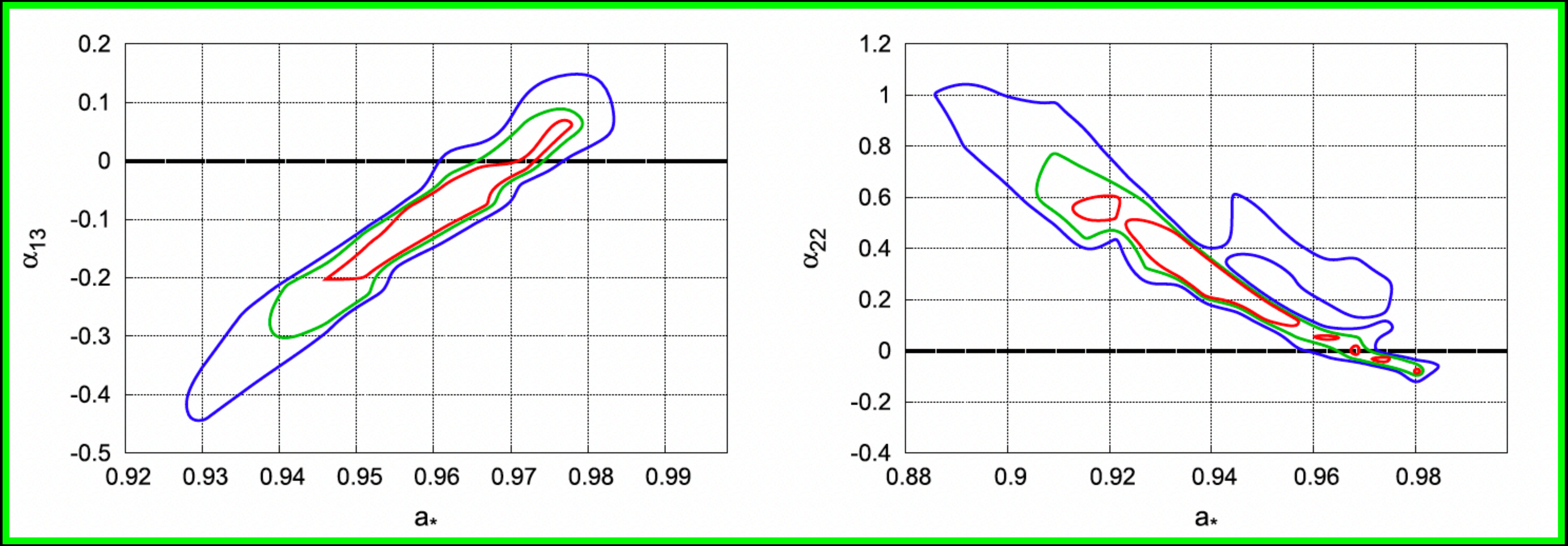
- LMC X-1 (Tripathi et al. 2020), RXTE



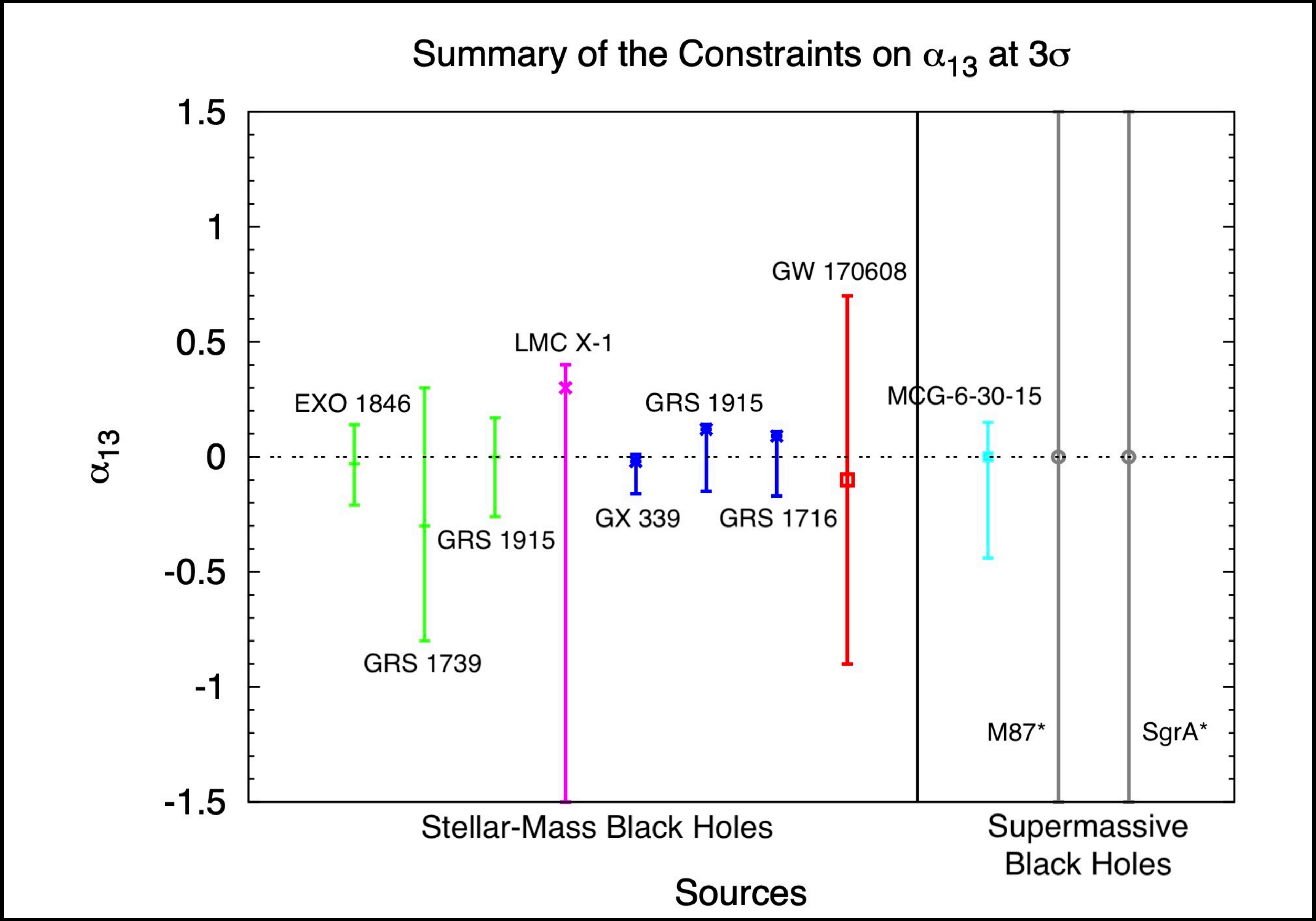


Analysis of Reflection Features

- MCG-6-30-15 (Tripathi et al. 2019), XMM+NuSTAR



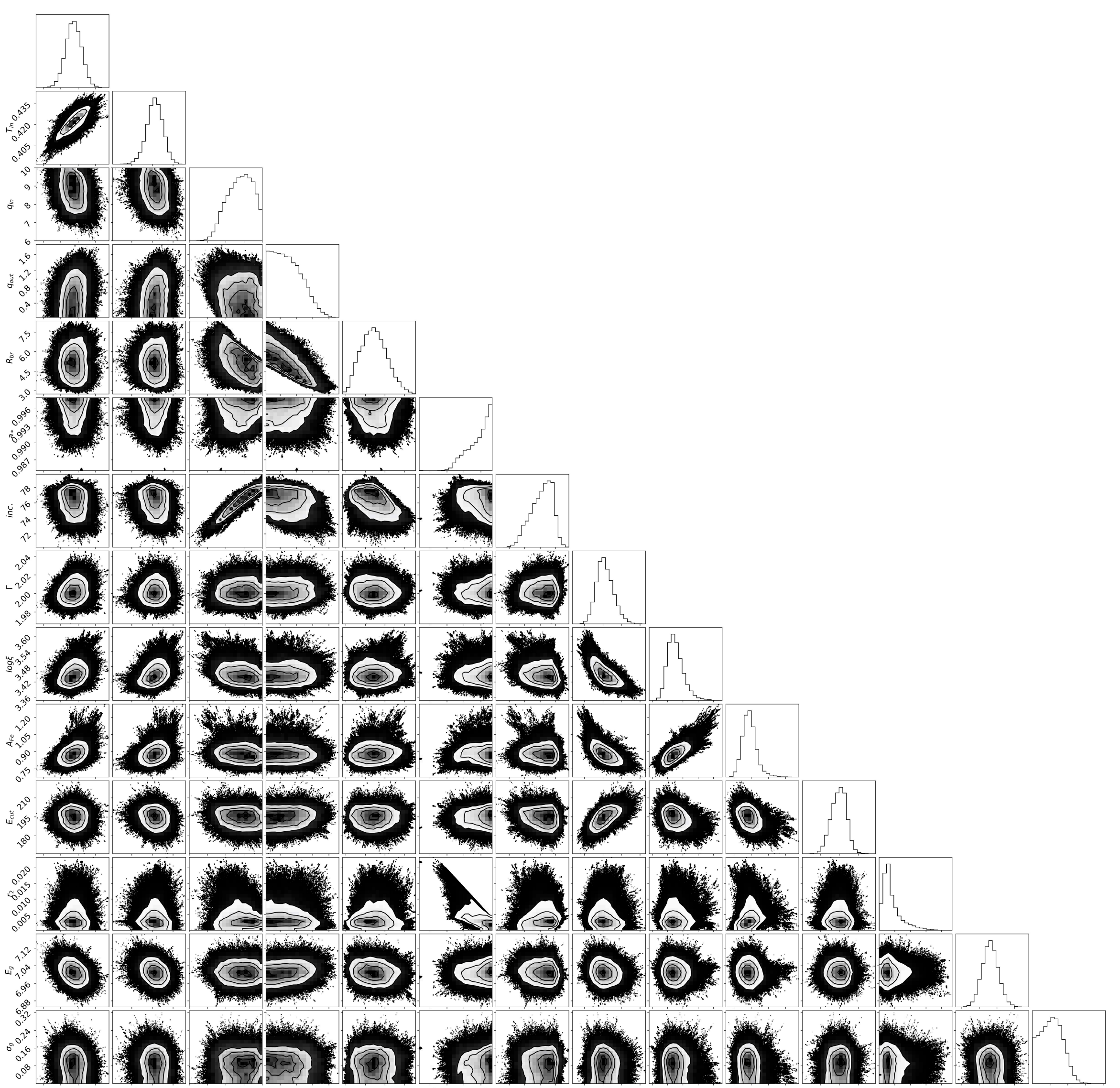
Summary: X-ray, GWs, VLBI

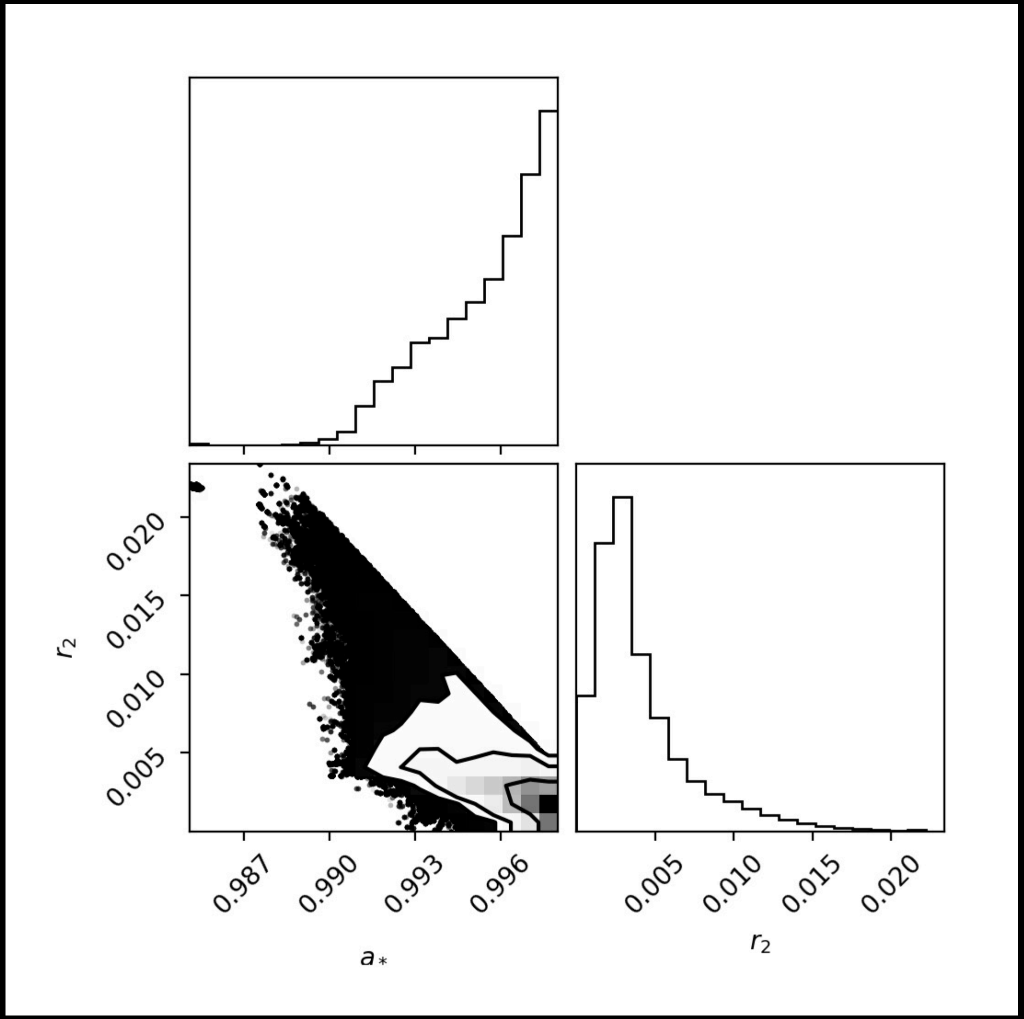


Results:
Tests of Specific Gravity Models

Einstein-Maxwell-Dilaton-Axion Gravity

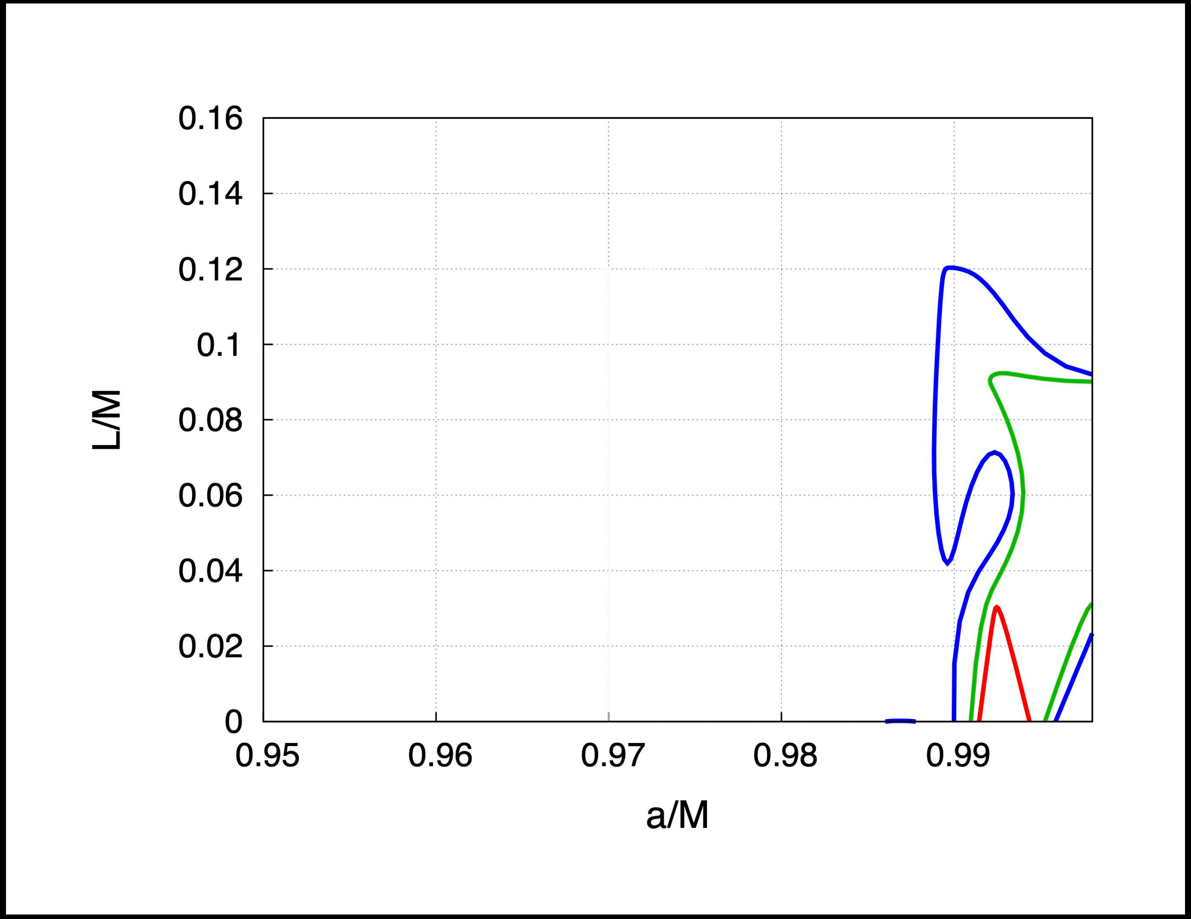
- Tripathi et al. 2021
- EXO 1846-031 (NuSTAR)
- Constraint: $r_2 < 0.011$ (90% CL)





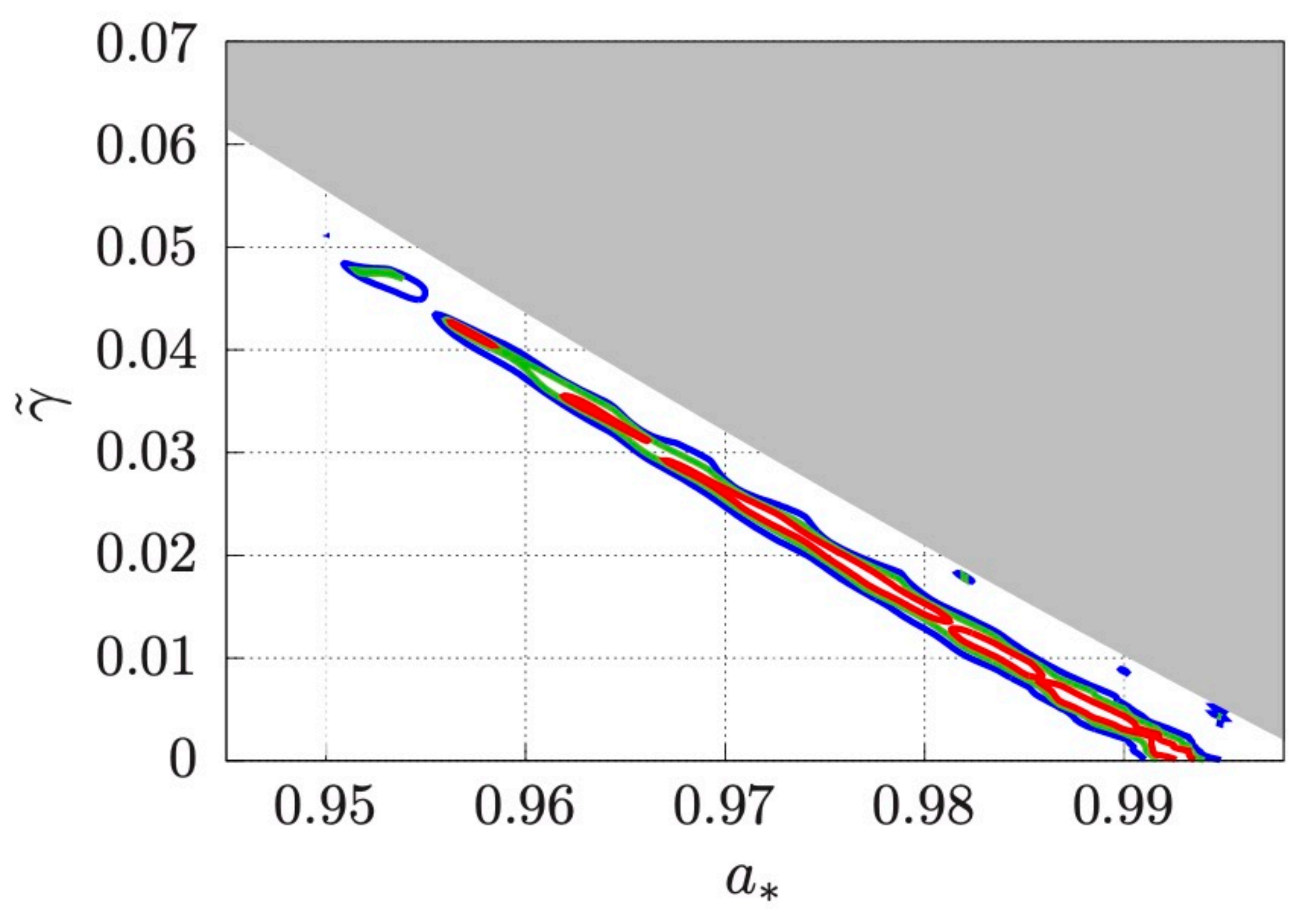
Conformal Gravity

- Zhou et al. 2018, 2019
- GS 1354-645 (NuSTAR)
- Constraint: L/M < 0.12 (99% CL)



Asymptotically Safe Quantum Gravity

- Zhou et al. 2021
- GRS 1915+105 (Suzaku)
- Constraint: $\gamma < 0.047$ (90% CL)



Accuracy of GR Tests with X-ray Data

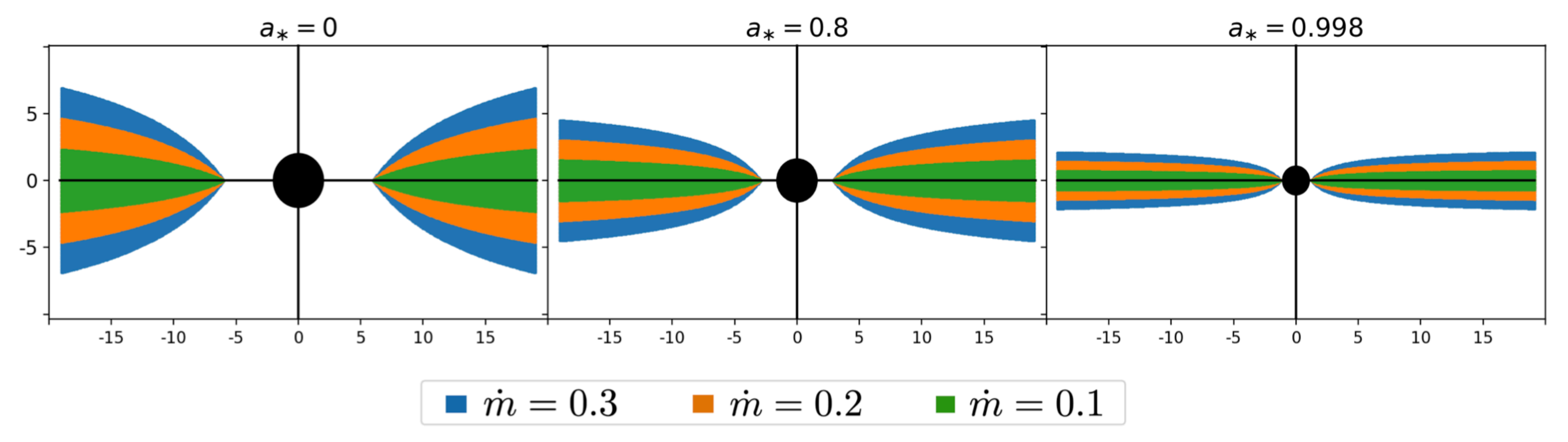
Source Selection

Source selection for X-ray reflection spectroscopy:

- High spin ($a > 0.9$)
- Compact corona close to the black hole
- Prominent broadened iron line
- $L \sim 0.05\text{-}0.30\ L_{Edd}$
- Bright source
- Constant flux
- High resolution at the iron line + hard X-ray band (e.g. XMM+NuSTAR)

Thickness of the Disk

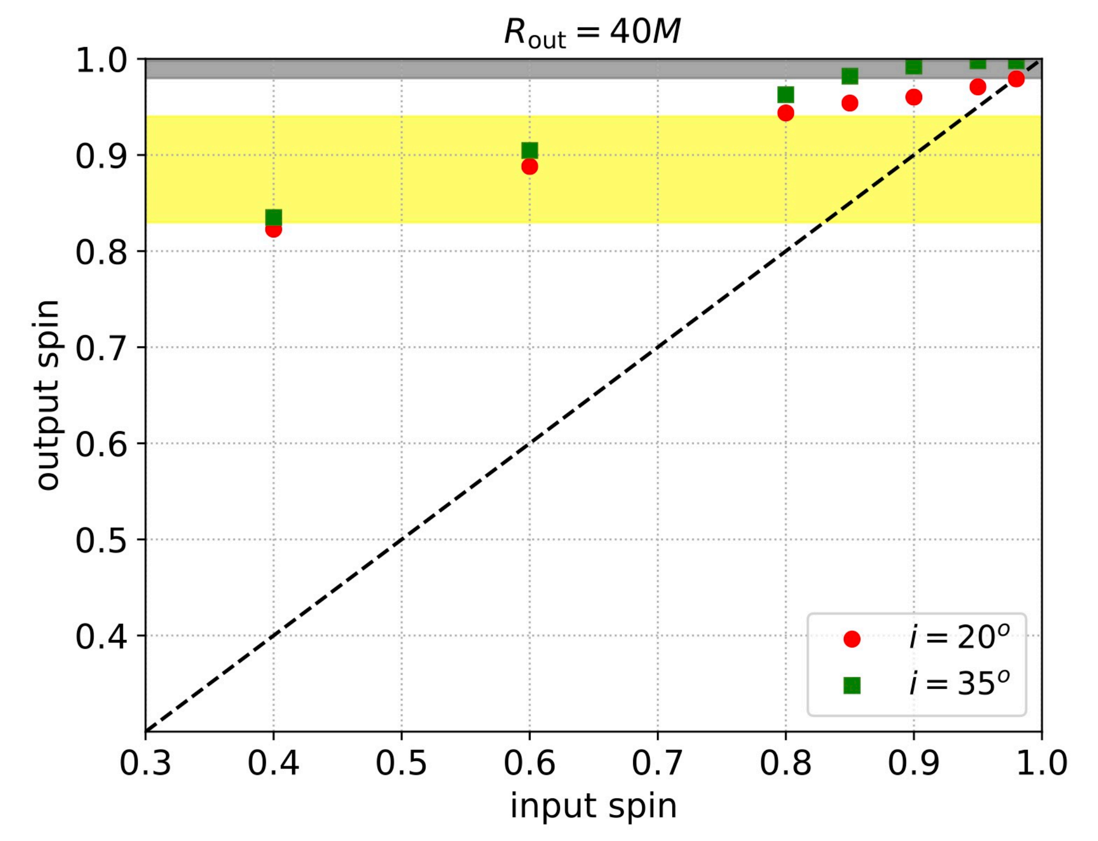
- Thin disks of finite thickness
- Abdikamalov et al. 2020 (model, GRS 1915+105)
- Tripathi et al. 2021 (MCG-6-30-15, EXO 1846-031)
- Jiang et al. 2022 (lamppost corona, MCG-6-30-15)

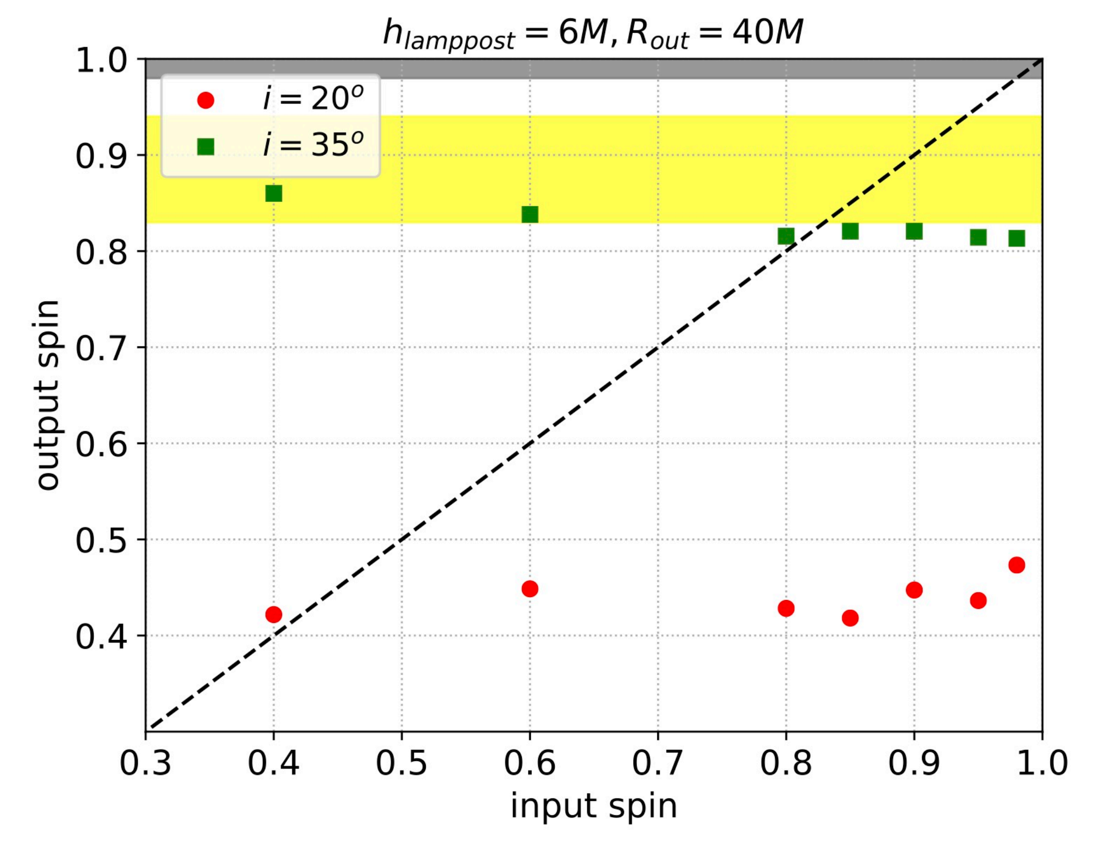


Conclusion: no significant impact on the parameter estimate for disks with high radiative efficiency

Thickness of the Disk

- Thick disks
- Riaz et al. 2020a, 2020b

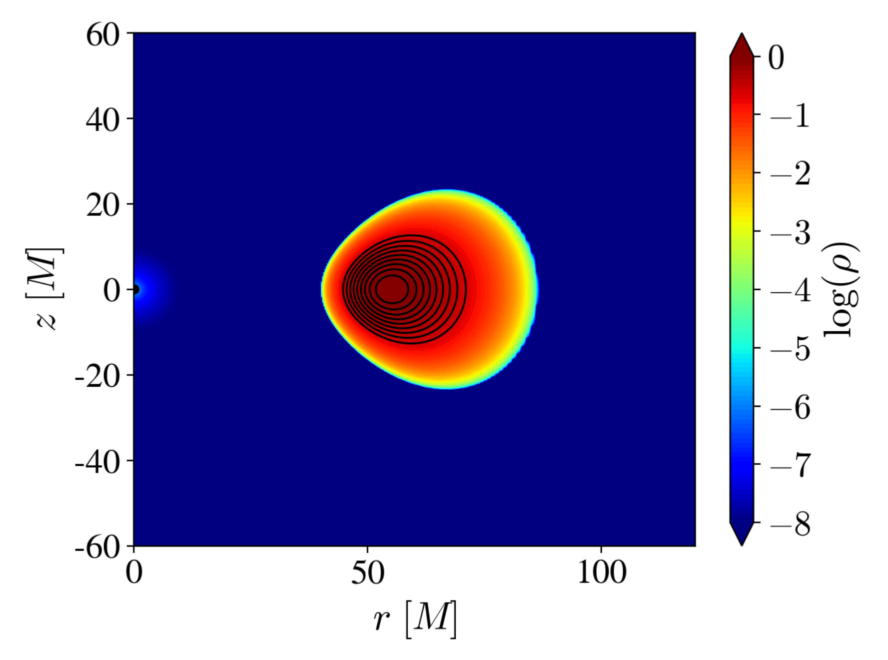


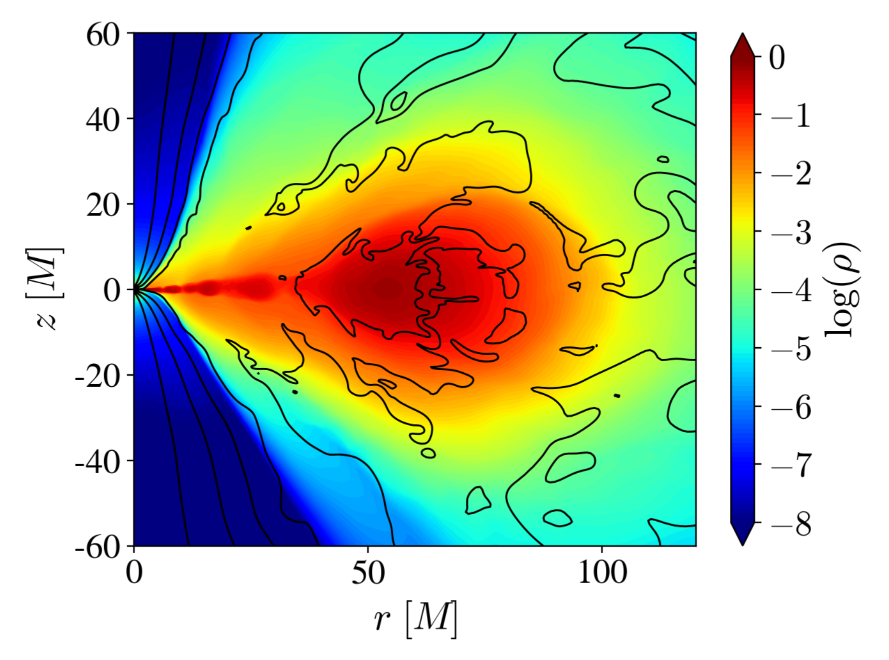


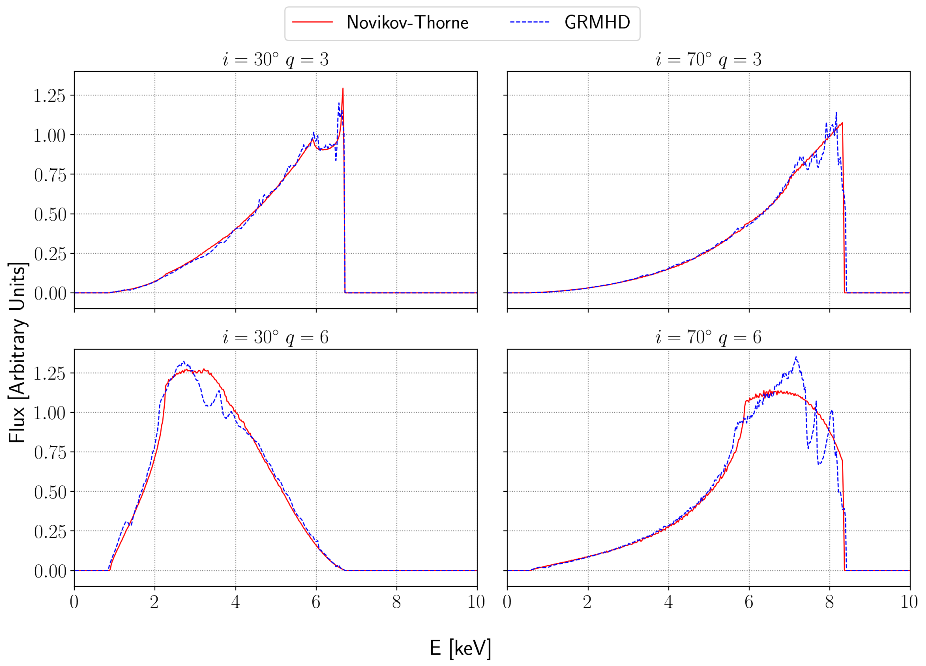
Conclusion: large systematic uncertainties, wrong measurements

GRMHD-Simulated Thin Disks

- Shashank et al. 2022







Conclusion: we recover well the input parameters

Concluding Remarks

Past/Present Work

- Models: `relxill_nk`, `nkbb`

- Public on GitHub: https://github.com/ABHModels

- Agnostic tests

- Tests on specific theories of gravity

Future Work

- More sophisticate astrophysical model (necessary to analyze the data of the next generation of X-ray missions)

- Tests of atomic physics and values of fundamental constants in the strong gravitational fields of black holes

Thank You!